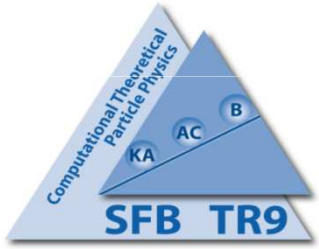
# Higgs production via vector-boson fusion at NNLO in QCD

**Paolo Bolzoni**


**In collaboration with F. Maltoni, S. Moch, M. Zaro** **arXiv:1003.4451[hep-ph]**

**Loopfest IX , 21-23 June 2010, Stony Brook University**

# Introduction and motivations

# Motivations for NNLO

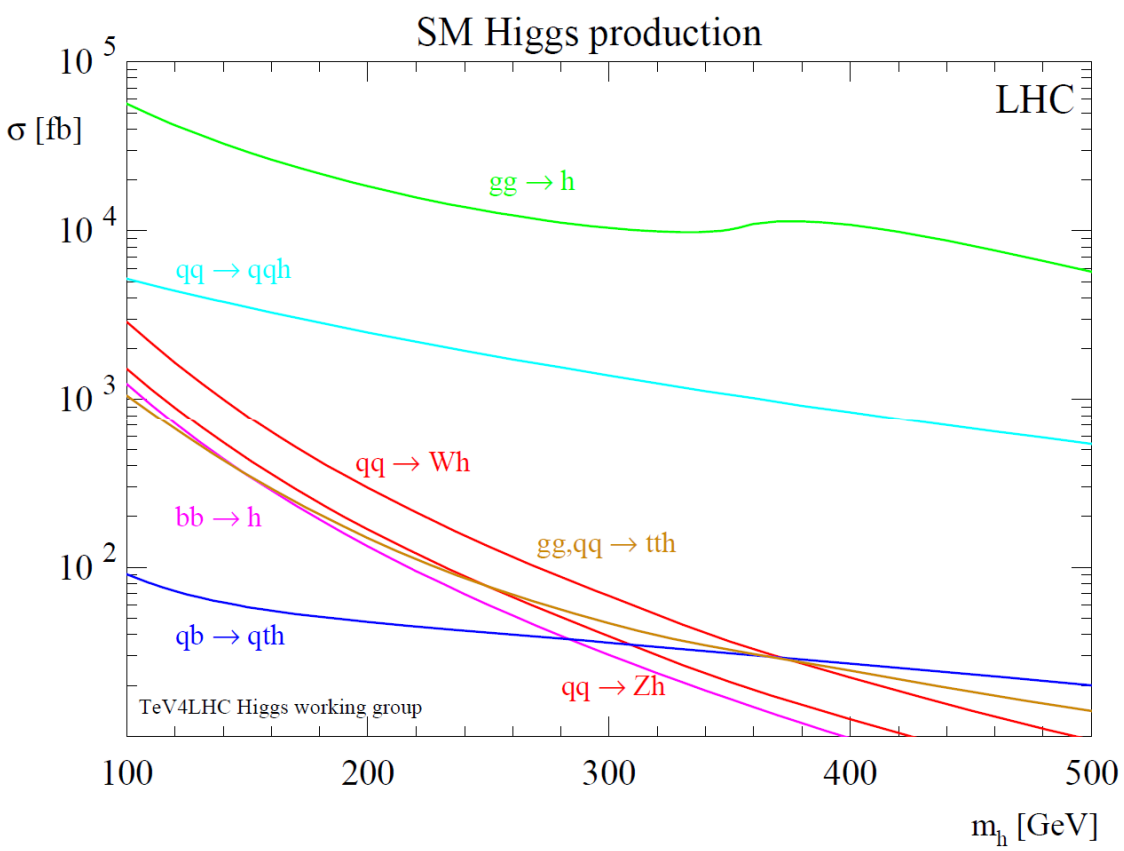
**The search for the Higgs demands:**

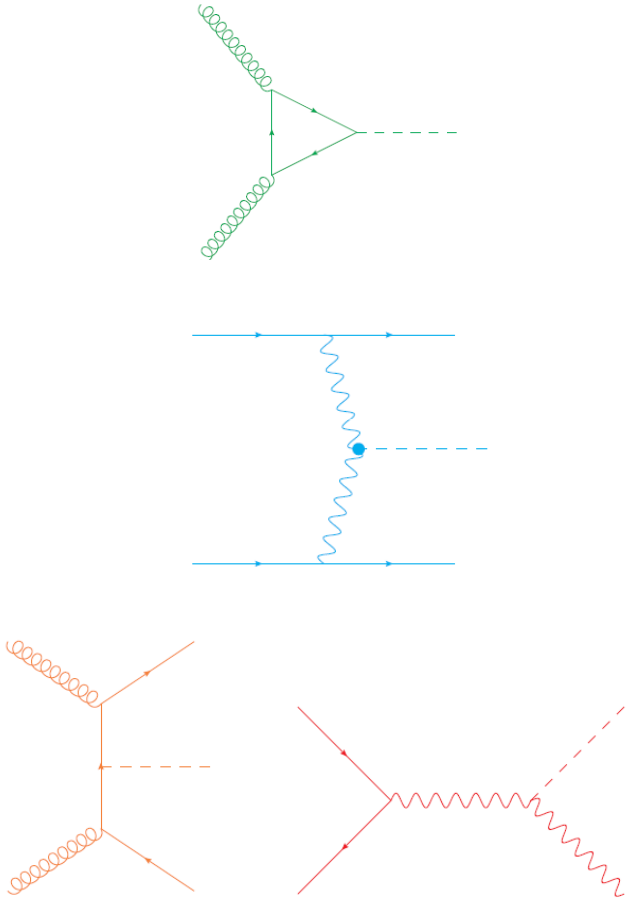
- **Its existence**
- **An estimate of the expected events**
- **Control over the background noise**

**Then to investigate its properties we need:**

- **A determination of the cross section as precise as possible**
- **The NLO already gives a reliable estimation of the cross section**
- **As will be shown at NNLO there is a significant improvement on the theoretical uncertainties from 10-15% down to 1-2%**

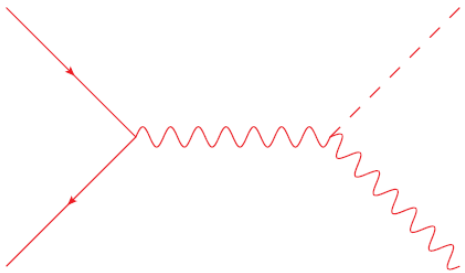
# Higgs boson production channels

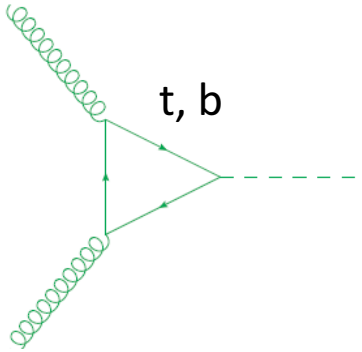


**VBF is the second most important production mechanism**

# Higgs-Strahlung and gluon fusion at NNLO

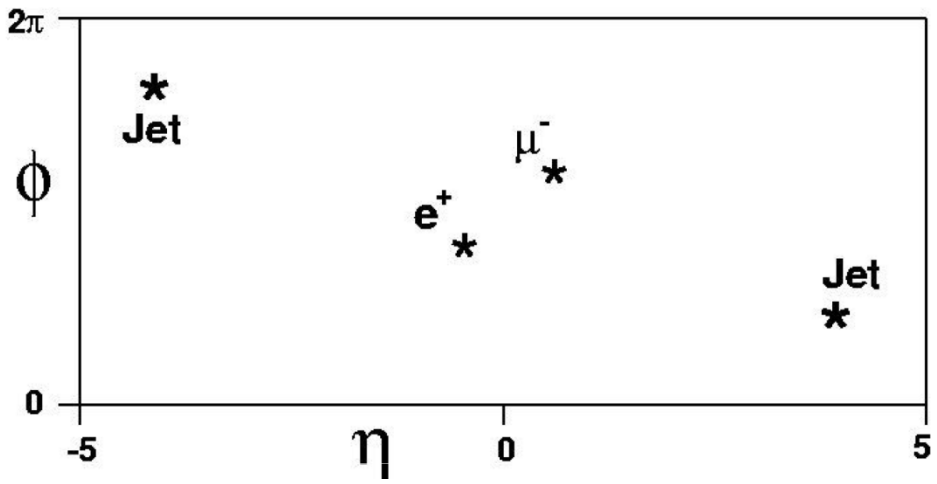





**Higgs-Strahlung computed at NNLO**
[O. Brein, A. Djouadi, R.V. Harlander (2004)]

**Latest updates of gluon fusion at NNLO with the inclusion of finite top mass effect.**
[A. Pak, M.Rogal, M.Steinhauser; R.V. Harlander, H. Mantler, S. Marzani, K.J. Orezen ]

# The VBF signal

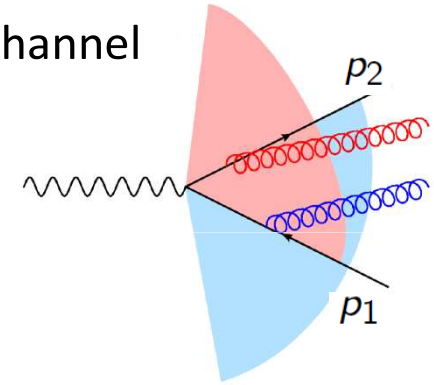



- Two hard tagging jets
- Large rapidity separation between jets
- Very small hadronic activity between jets
- Higgs decay in the central rapidity region

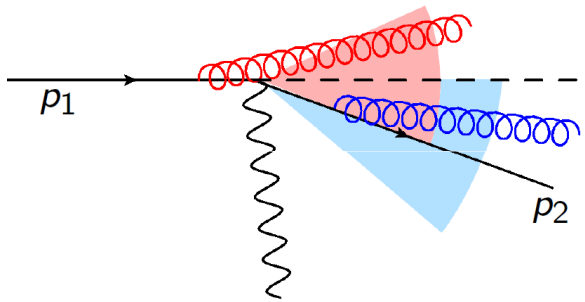
# Hadronic activity in VBF

**Angular ordering for the dominant soft gluon emission: the avaraged azimuthal emission is confined in a cone given by the angle between the emitter and the spectator**

s-channel




t-channel in VBF

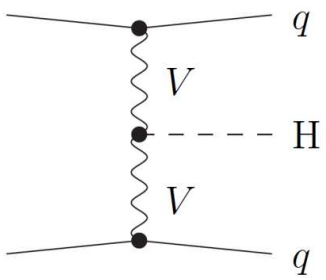



$$\sim \frac{1}{(p_1+p_2)^2} = \frac{1}{s} = \frac{1}{4E_{cm}{}^2}$$

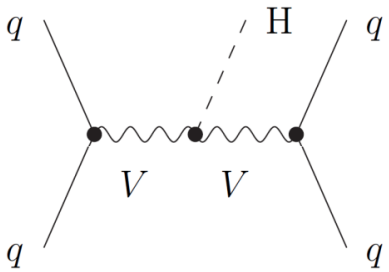
$$\sim \frac{1}{(p_1-p_2)^2 - M_V{}^2} = \frac{-1}{M_V{}^2 + 2E_1E_2(1-\cos\vartheta_{12})}$$

- **The t-channel propagator dominates for small $\vartheta_{12}$**
- **Soft gluon radiated at $\vartheta_g < 2\vartheta_{12}$**

# The VBF is a well defined process by itself

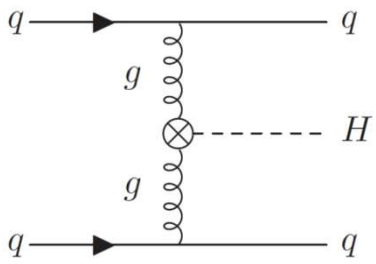



**The VBF has interferences with other processes at LO but also at higher orders**




**The interference with the Higgs associated production is at the per mil level already at LO in QCD**

[M. Ciccolini, A. Denner, S. Dittmaier]




**At higher orders the interference with the gluon fusion process is well below the percent level**

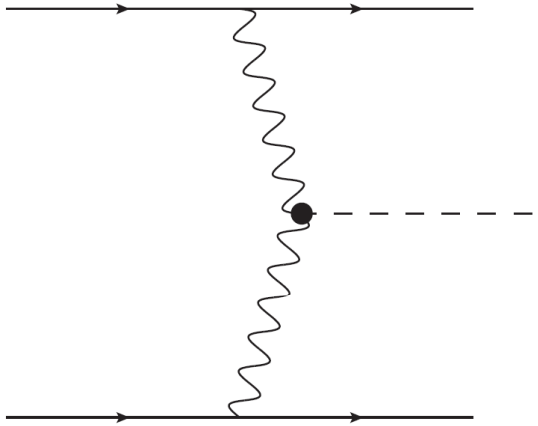
[J.R. Andersen, T.Binoth, G. Heinrich, J.M. Smillie]

**VBF can be defined up to an ambiguity of 1% which sets the target precision for theoretical predicions**

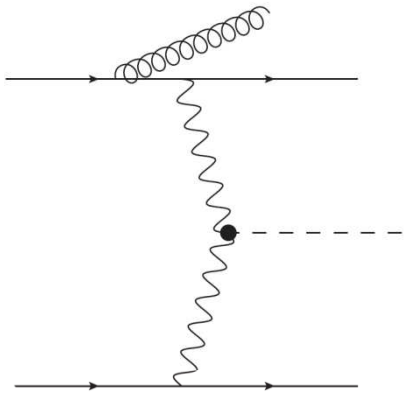
# The computation

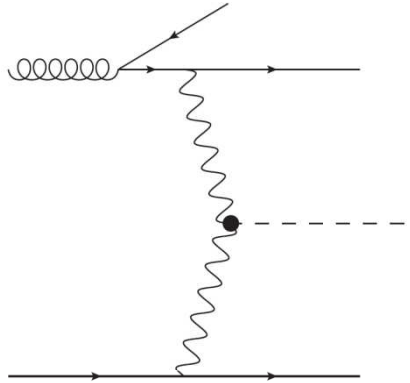
# The structure function approach at NLO

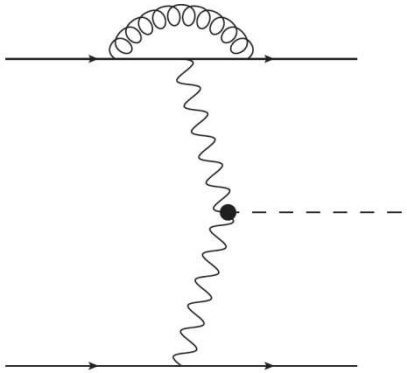
## LO

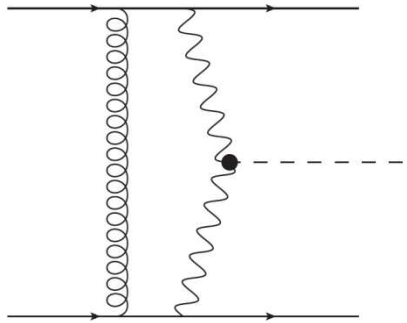


## NLO corrections



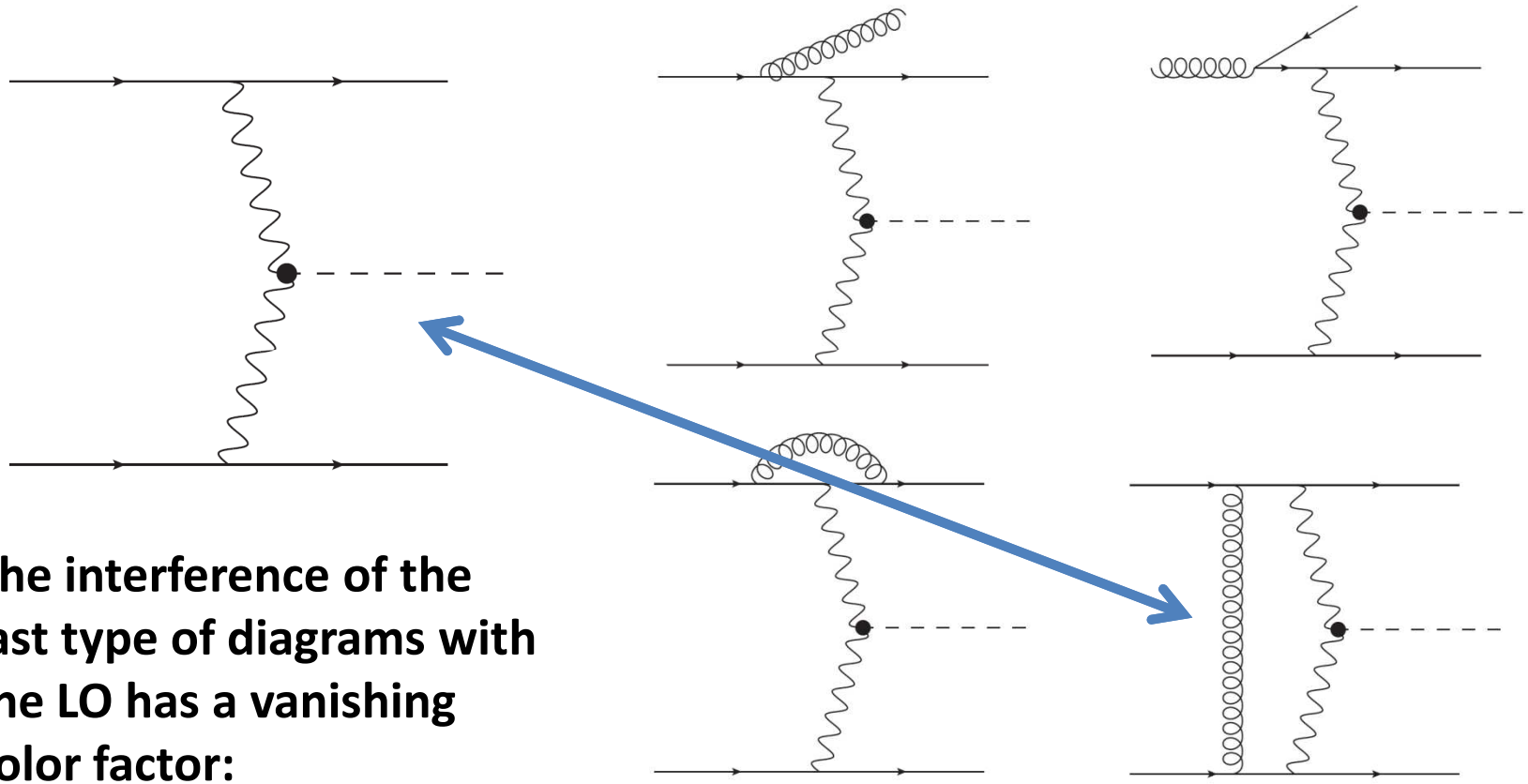






# The structure function approach at NLO

**LO** **NLO corrections**

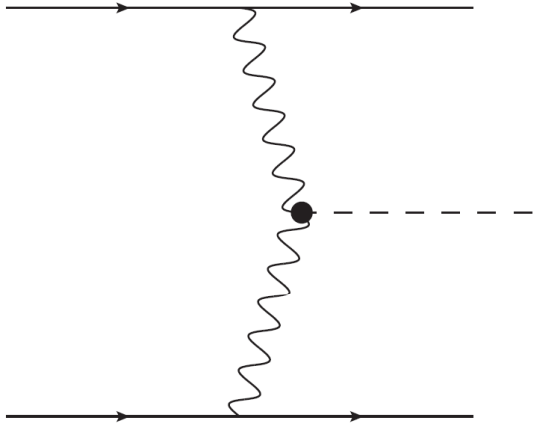


**The interference of the last type of diagrams with the LO has a vanishing color factor:**

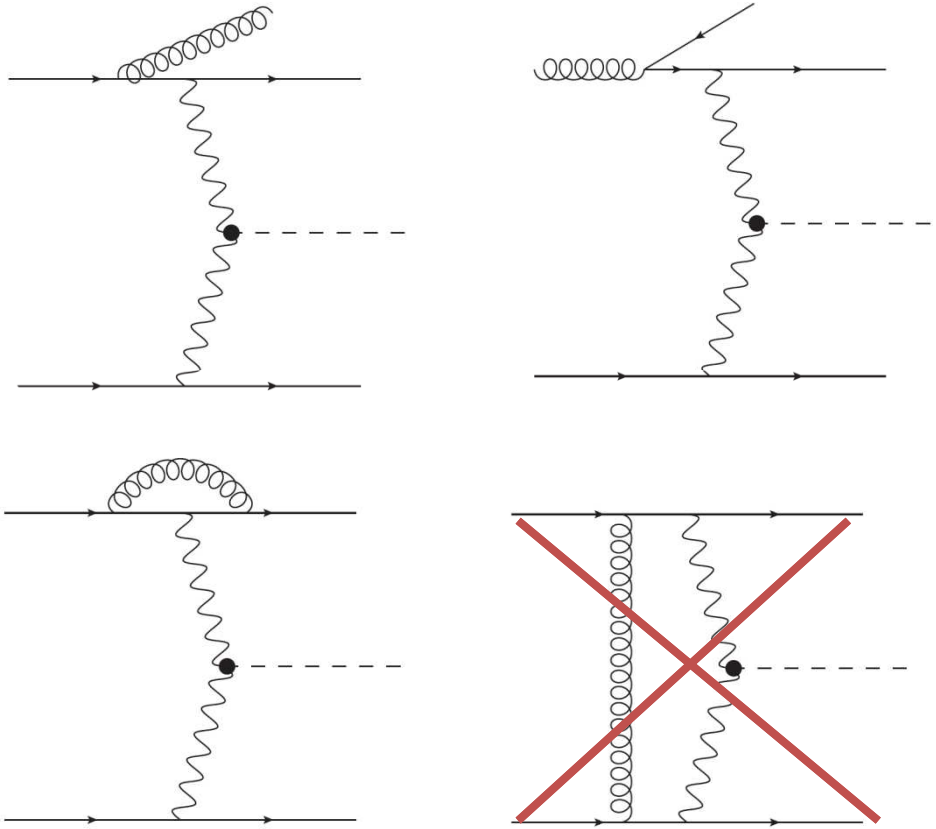
$$\delta_{ij} t^{a}_{ji} \delta_{ml} t_{lm}{}^{a} = [Tr(t)]^2 = 0$$

# The structure function approach at NLO

## LO

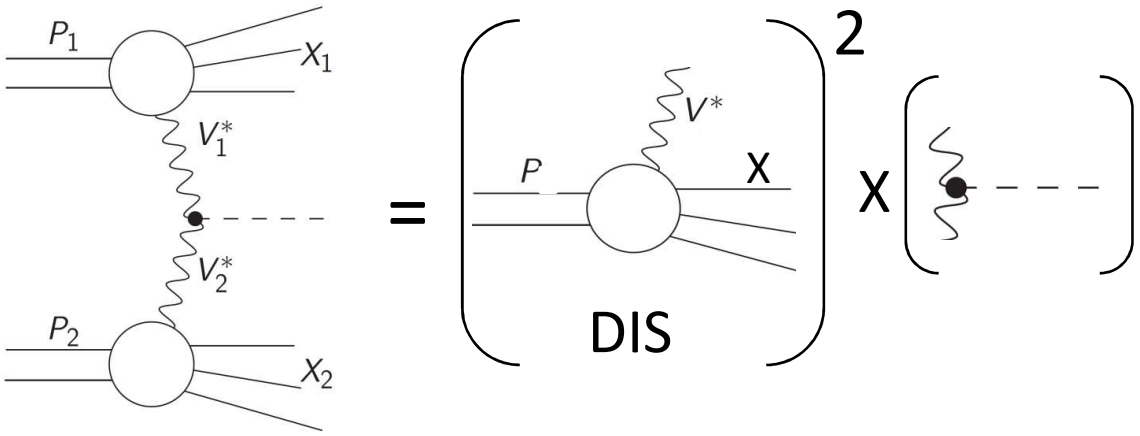


## NLO corrections



**Hence we can neglect the diagrmas with a gluon exchange in the t-channel and the upper and lower lines remain independnet**

# The structure function approach at NLO cntd.




$$d\sigma = \frac{1}{S} G_F^2 M_{V_1}^2 M_{V_2}^2 \frac{1}{(Q_1^2 + M_{V_1}^2)^2} \frac{1}{(Q_2^2 + M_{V_2}^2)^2} W_{\mu\nu}^{DIS}(x_1, Q_1^2) \mathcal{M}_{VVH}^{\mu\rho} \mathcal{M}^{*\nu\sigma}_{VVH} W_{\rho\sigma}^{DIS}(x_2, Q_2^2)$$

$$\times \frac{d^3 P_{X_1}}{(2\pi)^3 2E_{X_1}} \frac{d^3 P_{X_2}}{(2\pi)^3 2E_{X_2}} ds_1 ds_2 \frac{d^3 P_H}{(2\pi)^3 2E_H} (2\pi)^4 \delta^4 (P_1 + P_2 - P_{X_1} - P_{X_2} - P_H)$$

**Hence the NLO knowledge of the DIS structure functions $F_1$, $F_2$ and $F_3$ is enough to compute the NLO VBF cross section**

**This factoritation exact at NLO is the so-called strucure function approach**

[T.Hahn, G. Valencia, S. Willenbrock]

# The structure function approach at NNLO

**At NNLO the structure function approach is NOT exact but it can be still considered a good approximation and the dominant contributions can be included in the NNLO structure functions**

$F_1, F_2, F_3$

[D.I.Kazakov, A.V. Kotikov, G.Parente, O.A.Sampaio, J.S.Guillen, E.B.Zijlstra, W.L. van Neerven, S.Moch, J.A.M.Vermaseren,A.Vogt]

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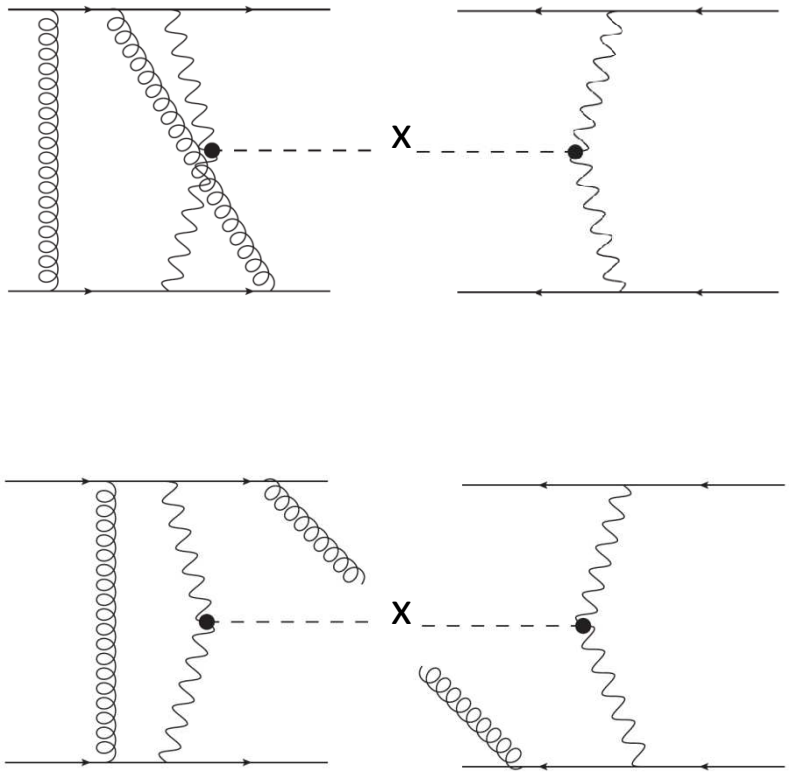
**The following types of contributions that in principle destroy the strucure function approach are:**

- **Double gluon-exchange in the t-channel (real and virtual)**
- **Single quark line (SQL) diagrams**
- **t/b loop diagrams**

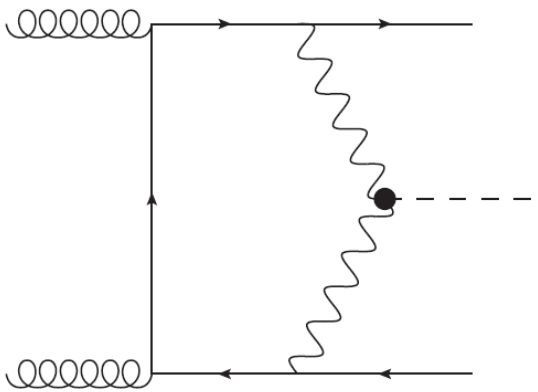
# The double-gluon exchange diagrams

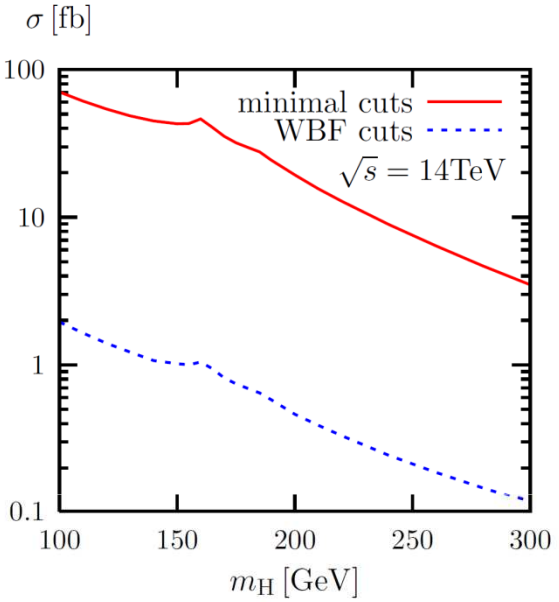



- **This is a gauge invariant class of diagrams**
- **IR and UV finite**
- **It is a color $(1/N_c)^2$ suppressed class with respect to the DIS$^2$ contributions**
- **They are also kinematically suppressed**

  [T.Figy, V. Hankele, D.Zeppenfeld, J. Blümlein, J.A.M. Vermaseren]

# The SQL diagrams

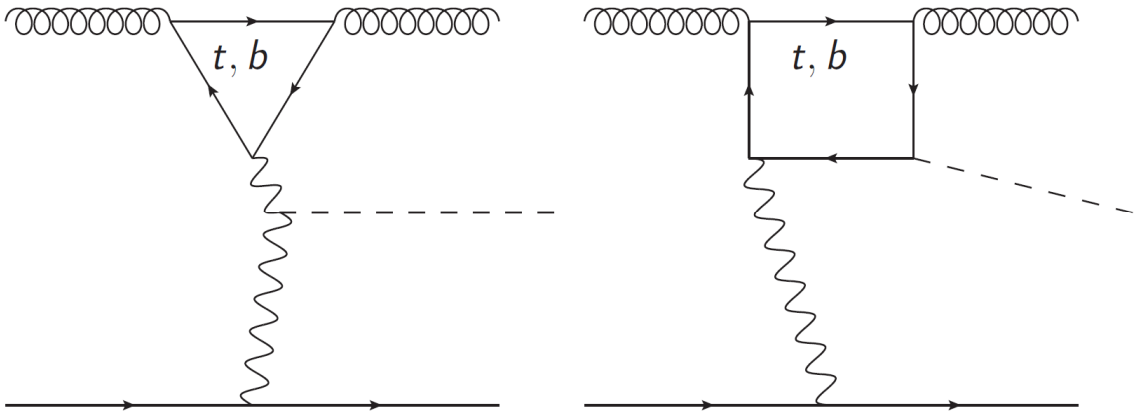





**Single quark line (SQL) contributions:"using a minimal set of cuts, the numerical impact of these terms is at the percent level with respect to NLO rate for WBF. Applying the so-called WBF cuts leads to an even stronger suppression, so that we do not expect a significant deterioration of the WBF signal by these color exchange effects"**

[R.V. Harlander, J. Vollinga, M.M. Weber arXiv:0801.3355[hep-ph]]

# The t/b loop diagrams

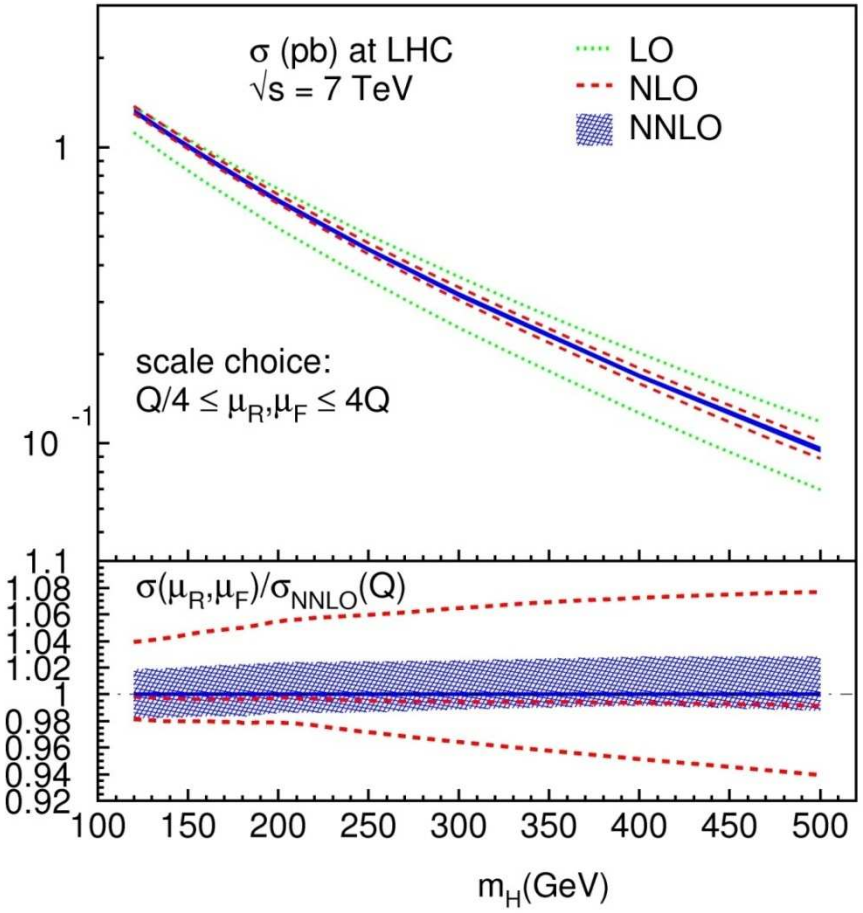


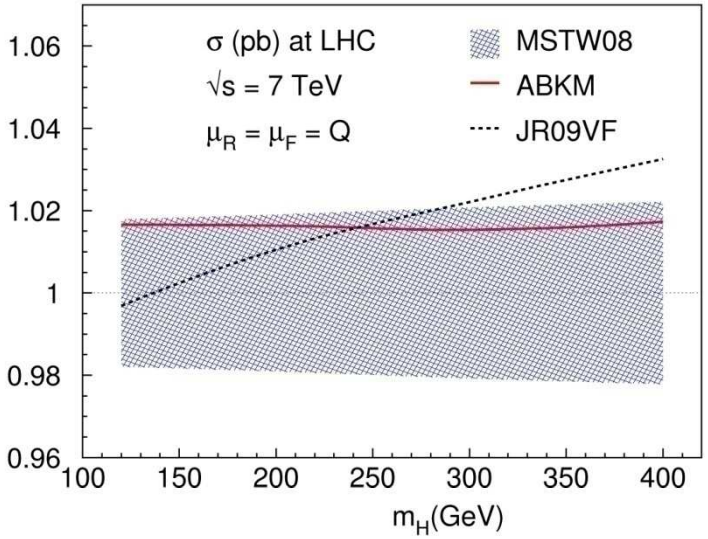

| $m_h$ (GeV) | 120 | 300 | 500 |
|---|---|---|---|
| 1.96 TeV | 3.87 E-6 (0.0690) | 2.52 E-7 (0.0054) | 1.50 E-8 (0.00042) |
| 7 TeV | 2.62 E-4 (1.235) | 7.89 E-5 (0.614) | 2.73 E-5 (0.088) |

- **Contribution from the triangle to the total VBF cross section well below the 1% (checked by two independent computations)**

# Results

# LHC @ 7 TeV

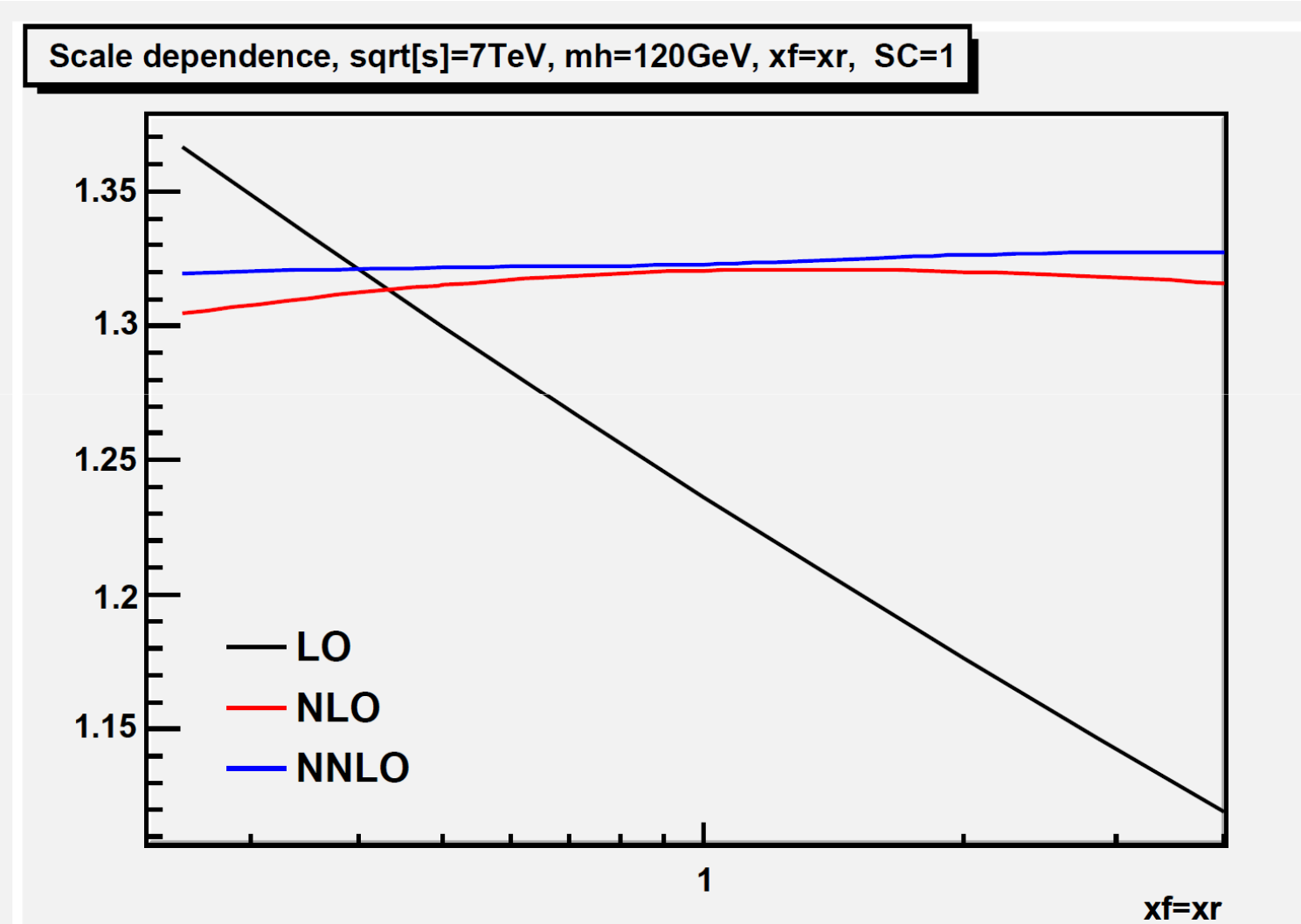


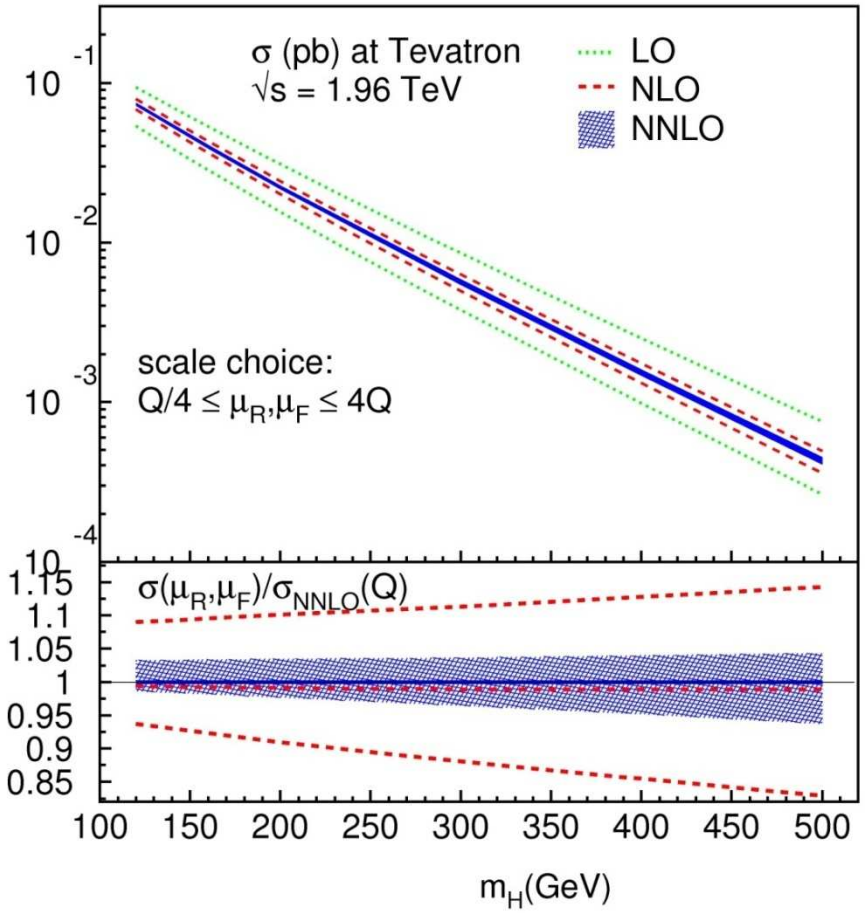

**The PDF error band MSTW08 is 2% and is compatible with other NNLO best fits (ABKM, JR)**

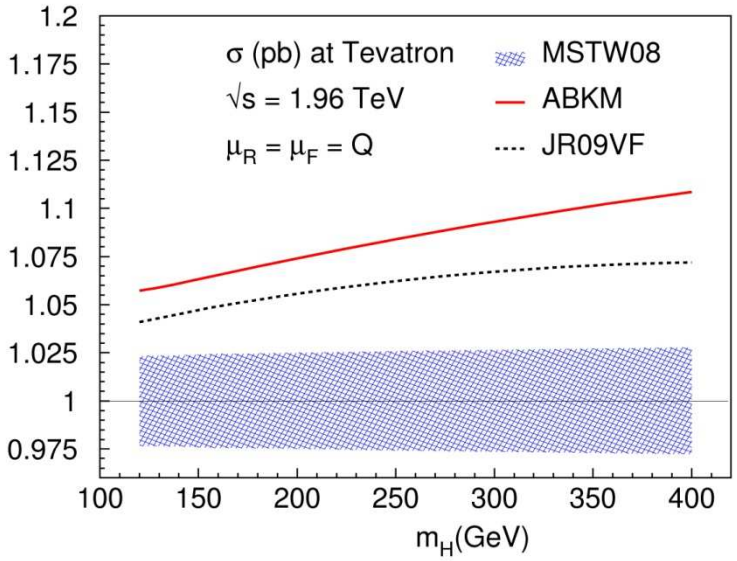
**The convergence of the perturbative series is well behaved**

# Theoretical uncertainties improvement



# Tevatron



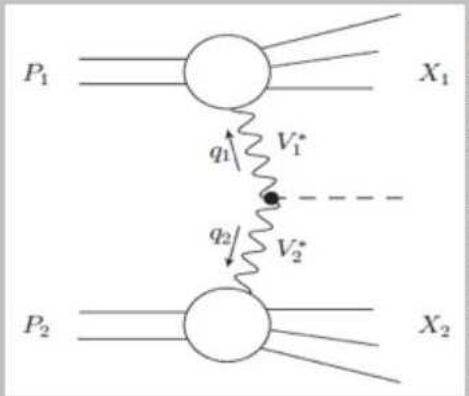

**In this case the difference between MSTW08 and ABKM and JR is due to larger uncertainties for the high-x quark PDFs**

[S. Alekhin, J. Blümlein, S. Klein, S. Moch arXiv:0908.2766[hep-ph]]

# VBF @ NNLO : Cross-section Calculator

by P. Bolzoni, F. Maltoni, S.-O. Moch and M. Zaro

alpha version v0.1 -- 10 April 2010




Higgs production in vector-boson fusion (VBF) is computed via a structure-function approach, as reported in ArXiv:1003.4451 [hep-ph].
This simple interface allows any registered user to obtain a cross section up to NNLO in QCD, including an estimate of the theoretical uncertaintes coming from scale variation and PDF uncertaintes.
The electro-weak parameters used for the cross-section computation are set to their respective PDG values (see the list here).
The code runs over the CP3-MadGraph cluster and might take up to a few hours depending on the actual request. An e-mail with the corresponding data file is sent to the user as soon as results are available. The possibility of requesting multiruns, i.e. runs corresponding to a series of Higgs mass values and/or collider energies, will be available soon upon e-mail request.
See the HNNLO web page by M. Grazzini for a similar tool for gg -> H.

New users are kindly asked to register here

| | | |
|---|---|---|
| Up to order: | NNLO | |
| Collider type: | p-p | |
| Center of mass energy: | 7000 | GeV |
| Higgs boson mass: | 120 | GeV |
| PDF set: | MSTW08 | |
| PDF uncertainities: | no | |
| Reference scale: | Q | Description |
| Scale uncertainities: | no | Description |

http://madgraph.phys.ucl.ac.be/vbf.html Submit

This is an alpha version. Pleae send comments/requests/bug reports to Marco Zaro (e-mail: Marco.Zaro AT uclouvain.be).

# Conclusions and outlooks

# Conclusions and outlooks

- **VBF is a promising channel for both the discovery and the precision measurment of the Higgs at LHC**
- **The structure function approach is a good tool to obtain NNLO cross section**
- **First NNLO VBF cross section**
- **Theoretical uncertainties lowered to 1-2%**
- **Need for a differential NNLO computation for the future**

# Extra slides

# Theoretical uncertainties estimate

**DIS structure functions:**

$$F_i(x, Q^2) = \sum_{j=0} \alpha_s^j(\mu_r^2) \, [C_i^j(Q^2, \mu_r^2, \mu_f^2) \otimes f(\mu_f^2)](x)$$

- $Q^2$ is the physical scale of the process
  (the DIS cross section depends on it)
- $\mu_{f,r}$ unphysical factorization and renormalization sclaes

**The theoretical uncertainties are estimated varying the two unphysical scales. This dependence tend to be compensated and hence the dep. of a order $\alpha^k$ computatio is of order $\alpha^{k+1}$**

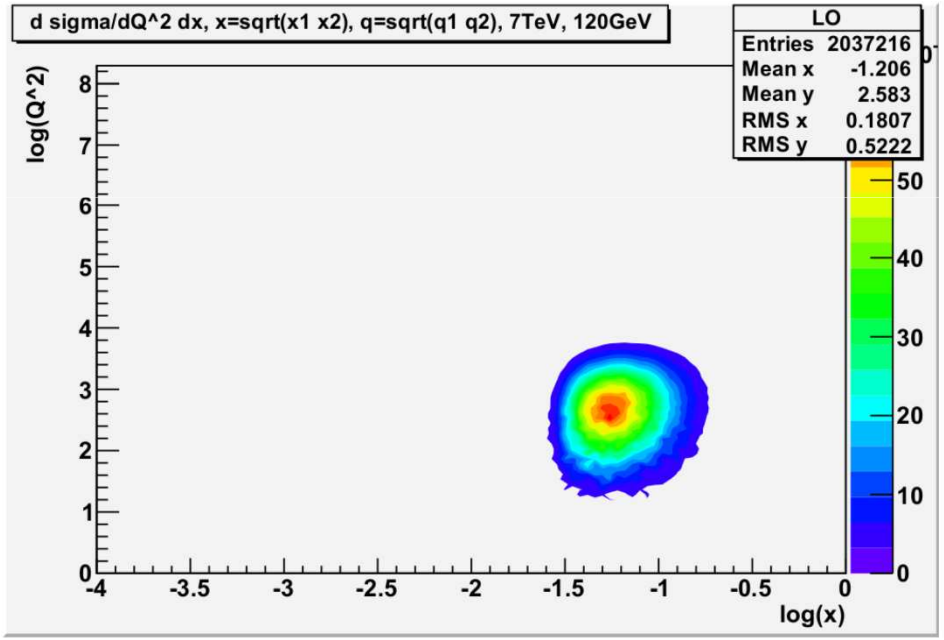
# Scale choices

**Two different sclaes have been used:**

$$\mu^2_{r/f} = x_{r/f}\, m_h^2 \ (\mathrm{SC}=0)$$

$$\mu^2_{r/f} = x_{r/f}\, Q^2 \ (\mathrm{SC}=1)$$

$$\frac{1}{4} \leq x_{r/f} \leq 4$$

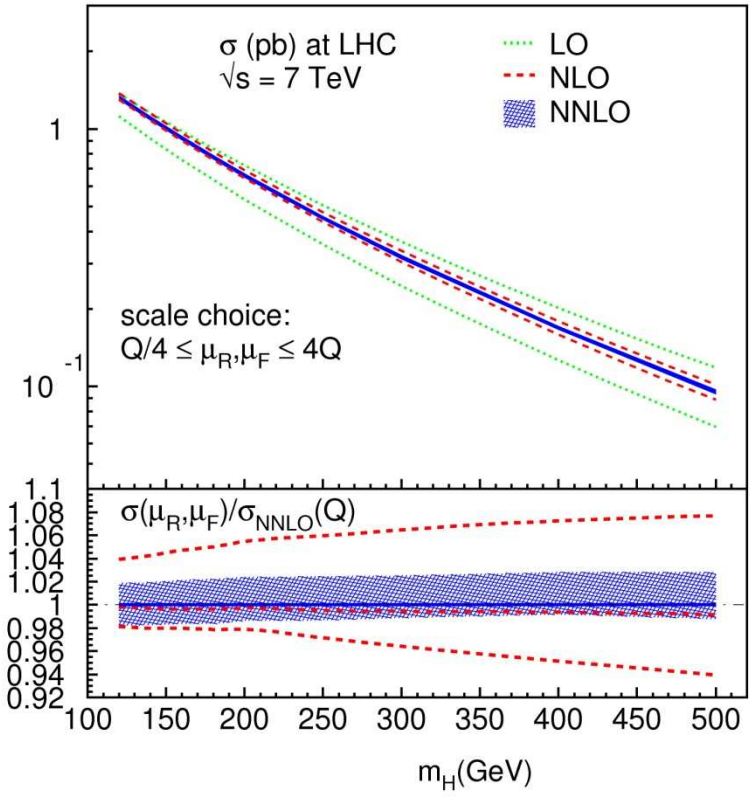


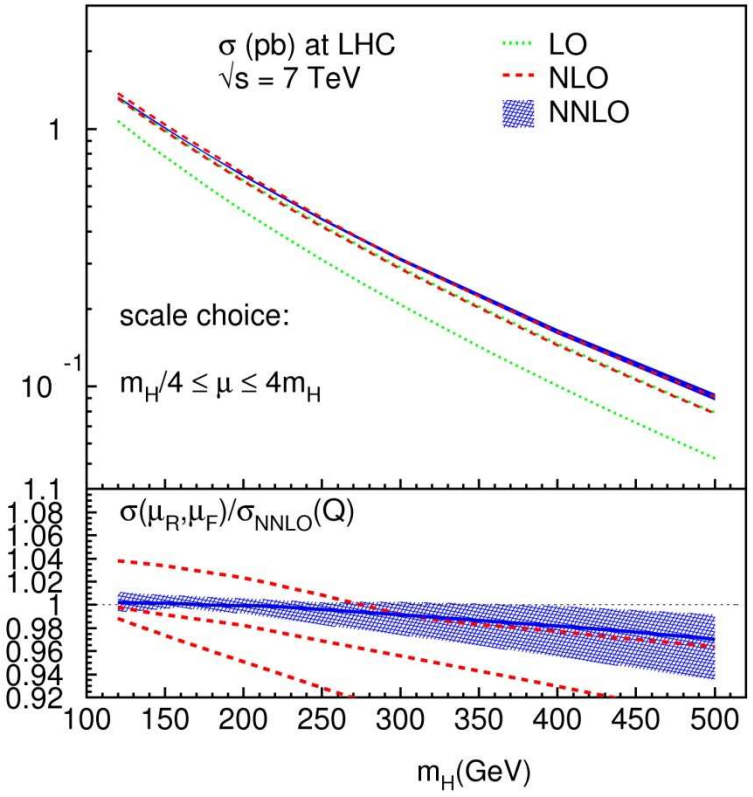

$$< Q^2 > \simeq (20\mathrm{GeV})^2$$

$$< x > \simeq 6 \cdot 10^{-2}$$

**The effective avaraged value of $Q^2$ is relatively low and so the hoice sc=1 looks more natural**

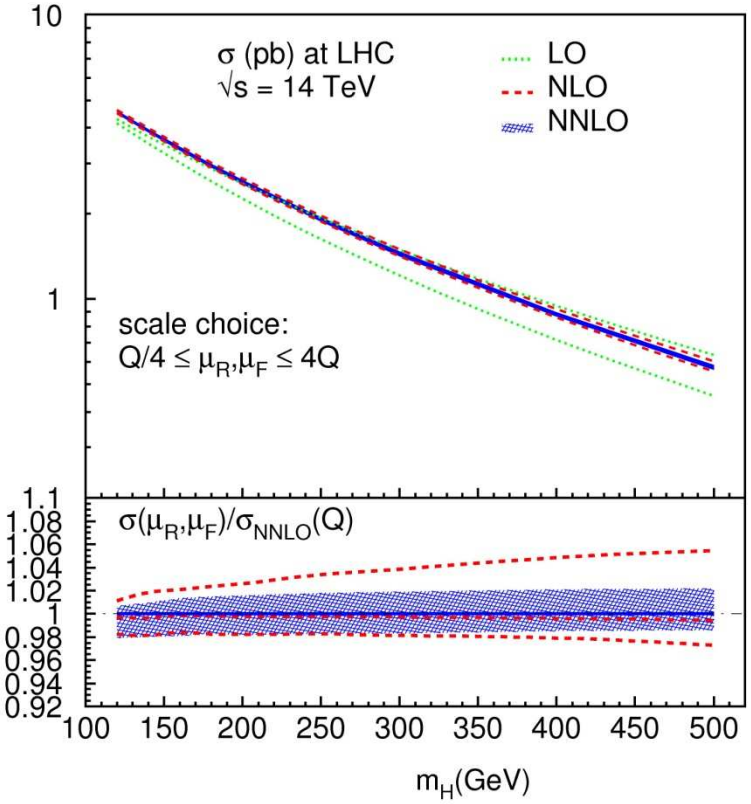
# At NNLO the two scale choices become equivalent

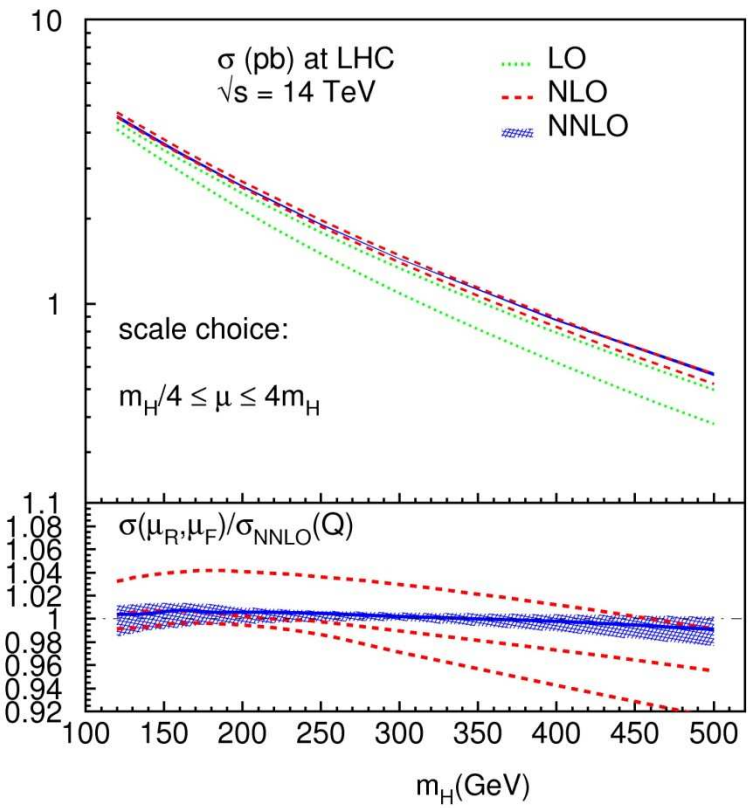



# LHC @ 7 TeV

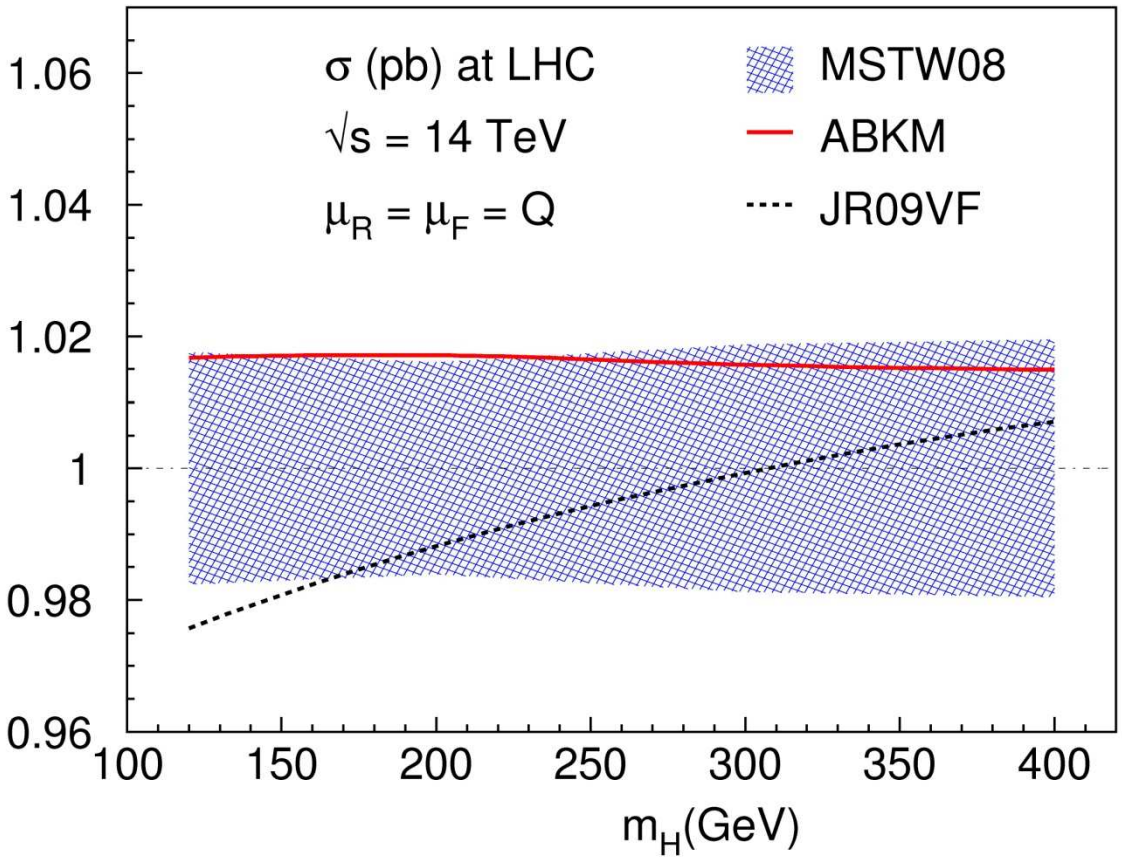
# At NNLO the two scale choices become equivalent

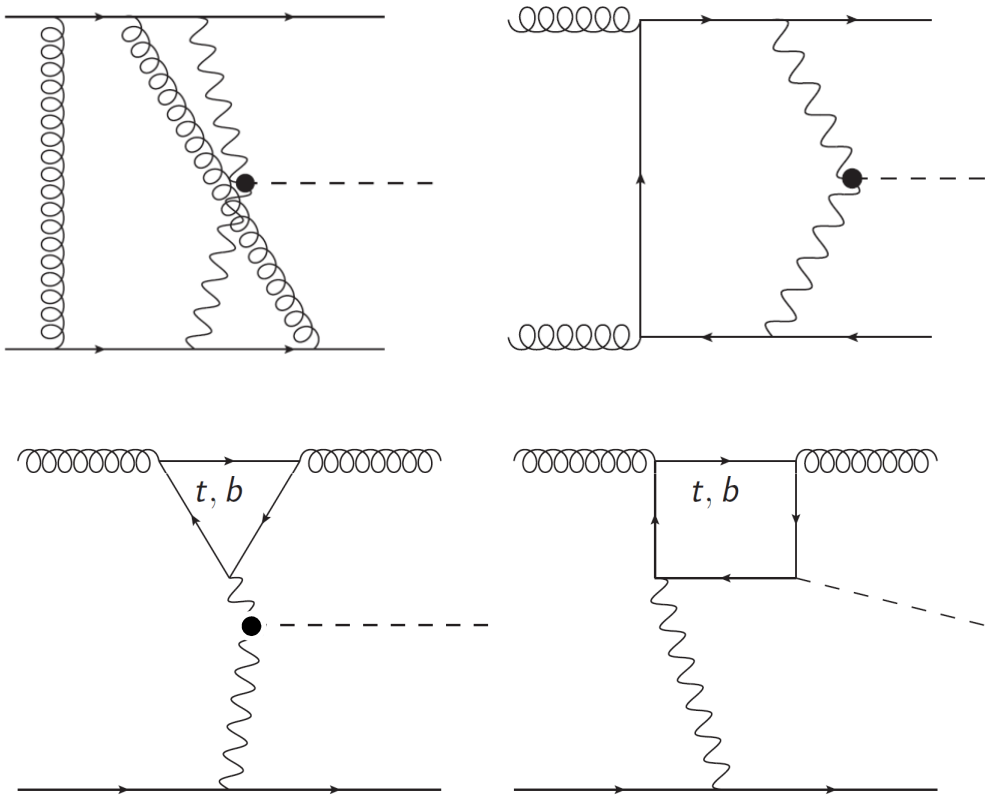



## LHC @ 14 TeV

# PDF uncertainties LHC @ 14 TeV

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